

Apparatus and Method for Sampling Timing Compensation in Multi-carrier System

Background of the Invention

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(a). Field of the Invention

The present invention relates in general to a communication system, and more particularly to an apparatus for estimating and compensating sampling timing offset in a multi-carrier system and a method thereof.

(b). Description of the Prior Arts

In recent years, multi-carrier technology is widely applied to high-speed communication systems, such as asymmetric digital subscriber loop (ADSL), IEEE 802.11a/g wireless local area network (WLAN), etc. Fig.1 is a block diagram of a typical multi-carrier system 100. The transmitter of the multi-carrier system 100 first distributes the data under transmission into N frequency-domain subchannels ($N=2^n$, n is an integer) via a signal mapping unit 101, and maintains the orthogonality among the signals of each subchannel to prevent inter-carrier interference (ICI). Next, an inverse fast Fourier transform (IFFT) device 102 is used to transform the subchannel signals into time-domain signals, to which a guard interval (GI) is added by a GI adding device 103. Then, each of these time-domain signals is passed through a parallel-to-serial converter (P/S) 104 and a digital-to-analog converter (DAC) 105, and then transmitted via a channel 106. The receiver of the multi-carrier system 100 first uses an analog-to-digital converter (ADC) 107 to sample the received time-domain signals. Next, the guard interval of the sampled signals is removed by a GI removing unit 109. The result thereof is provided to a serial-to parallel converter (S/P) 110, and then a fast Fourier transform (FFT) device 110 is used for transforming to frequency-domain signals. Last, the receiver compensates these frequency-domain signals by a channel compensator 112 and performs signal demodulation via a signal demapping unit 113 to recover to the original transmitted data.

A set of N-point IFFT output is typically called a symbol. Since the channel impulse response (CIR) is usually not ideal, a received symbol after passing through the channel 106 would impact the reception of subsequent symbols, i.e. inter-symbol interference (ISI). To prevent ISI, an additional guard interval (GI) is added between two symbols. Two typical ways to implement the guard interval are zero-padding (ZP) and cyclic prefix (CP). In ZP, a string of zero is added as the guard interval and energy efficiency is thus improved. In CP, a latter portion of a symbol is copied and put before the symbol as the guard interval. CP can reduce the ICI resulted from the channel impulse response. The circuits 103 and 109 of Fig.1 are used to add and remove the guard interval respectively.

When demodulating the received time-domain signals, the receiver of the system 100 needs to transform them into frequency-domain signals by the FFT device 111 and performs the demodulation within each subchannel respectively. If synchronization error exists in the time-domain signals inputted to the FFT device 111, then additional ICI and phase rotation would be generated in the outputted frequency-domain signals to damage the orthogonality of the outputted frequency-domain signals. For a multi-carrier system, the synchronization error mainly results from sampling frequency offset and sampling phase error. Besides the additional ICI and phase rotation, the sampling frequency offset would generate an accumulated sampling timing offset, which may cause ISI to degrade the system performance.

In view of this, the present invention provides an apparatus and a method that can estimate and compensate the accumulated sampling timing offset by using pilot signals of a symbol, thereby upgrading the performance of a multi-carrier system.

Summary of the Invention

The present invention is generally applied to a communication system which encodes data as symbol signals at the transmitter and transmits the symbol signals via a plurality of subchannels. The symbol signal includes at

least two pilot signals. The subchannels include at least two pilot subchannels for transmitting a corresponding one of the pilot signals. The pilot signal is predetermined, and the present invention employs it to estimate and compensate sampling timing offset, thereby preventing the sampling timing offset from impacting signal demodulation at the receiver of the communication system.

Accordingly, in attainment of the aforementioned object, the present invention provides an apparatus for sampling timing compensation at the receiver of the communication system. The apparatus includes: a pilot subchannel estimator for generating an estimated frequency response of the symbol signal for the pilot subchannel according to the corresponding pilot signal; a timing offset estimator, coupled to the pilot subchannel estimator, for generating an estimated sampling frequency offset according to the estimated frequency responses of both the symbol signal and a following symbol signal for the pilot subchannels, and calculating an accumulated timing offset according to the estimated sampling frequency offset; and a phase rotator, coupled to the timing offset estimator, for performing sampling timing compensation according to an accumulated phase rotation corresponding to the accumulated timing offset.

In another aspect, the present invention provides a method for sampling timing compensation used at the receiver. The method includes: generating an estimated frequency response of the symbol signal for each of the pilot subchannels according to the corresponding pilot signal; generating an estimated sampling frequency offset according to the estimated frequency responses of both the symbol signal and a following symbol signal for the pilot subchannels; calculating an accumulated timing offset according to the estimated sampling frequency offset; and performing sampling timing compensation according to an accumulated phase rotation corresponding to the accumulated timing offset.

Brief Description of the Drawings

Fig.1 is a block diagram of a typical multi-carrier system.

Fig.2 is a block diagram showing a multi-carrier system with a sampling frequency offset.

Fig.3A is a diagram showing that the symbol boundary of a received symbol signal is shifted backwards.

5 Fig.3B is a diagram showing that the symbol boundary of a received symbol signal is shifted forwards.

Fig.4 is a block diagram of an apparatus for sampling timing compensation by adjusting a cyclic prefix remover according to the embodiment of the present invention.

10 Fig.5 is a flow chart of a method for sampling timing compensation by using the apparatus of Fig.4 according to the embodiment of the present invention.

15 Fig.6 is a block diagram of an apparatus for sampling timing compensation by adjusting a clock generator according to the embodiment of the present invention.

Fig.7 is a flow chart of a method for sampling timing compensation by using the apparatus of Fig.6 according to the embodiment of the present invention.

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Detailed Description of the Embodiments

The preferred embodiments of the present invention used in a multi-carrier system are described in detail below. Fig.2 is a block diagram showing a multi-carrier system with a sampling frequency offset. In Fig.2, since the sampling frequency $f_s = 1/T_s$ of the DAC at the transmitter is not
25 consistent with the sampling frequency $\hat{f}_s = 1/\hat{T}_s$ of the ADC at the receiver, a sampling frequency offset $\Delta f_s = f_s - \hat{f}_s$ is generated. Here T_s and \hat{T}_s denote the sampling intervals of the transmitter and receiver respectively. Accordingly, the sampling interval of the receiver can be represented as

$$\hat{T}_s = 1/(f_s - \Delta f_s) = T_s / (1 - \Delta) \approx T_s \cdot (1 + \Delta), \text{ where } \Delta = \Delta f_s / f_s = \Delta f_s T_s.$$

Due to the sampling frequency offset, a symbol boundary error is accumulated. Thus, the received signals at the receiver may suffer ISI, delay-rotor, and ICI, as shown in Fig.3A and 3B. Fig.3A is a diagram showing that the symbol boundary of the received symbol is shifted backwards. The backward shift of the symbol boundary results from a positive sampling frequency offset Δf_s , i.e. the sampling frequency of the transmitter is larger than that of the receiver. As shown in Fig.3A, in addition to ICI, the backward shift of the symbol boundary would result in ISI since the symbol covers parts of the following symbol. Fig.3B is a diagram showing that the symbol boundary of the received symbol is shifted forwards. The forward shift of the symbol boundary results from a negative sampling frequency offset Δf_s , i.e. the sampling frequency of the transmitter is smaller than that of the receiver. As shown in Fig.3B, in addition to ICI, the forward shift of the symbol boundary would result in an accumulated sampling timing offset τ which causes an accumulated phase rotation generated in each subchannel signal of the received symbol after performing FFT, i.e. a delay-rotor effect is generated.

Further, the influence of the sampling frequency offset on a symbol can be explained in terms of time domain and frequency domain. In the aspect of time domain, if time-domain signals of the symbol have $N+N_{GI}$ sampling points, where N is the number of points outputted from FFT and N_{GI} is the number of points of a guard interval, then there is a sampling timing offset of $\varepsilon = -(N + N_{GI})\Delta$ between the corresponding sampling points of two consecutive symbols. The sampling timing offset ε would result in a symbol boundary error in time domain, and cause an additional phase rotation $-\omega_k \varepsilon = 2\pi k \Delta \cdot (\frac{N + N_{GI}}{N})$ generated in the k -th subchannel signal of

the symbol, where $\omega_k = \frac{2\pi k}{N}$ is the carrier frequency of the k-th subchannel signal.

In the aspect of frequency domain, if assuming that the frequency response of the i-th subchannel is fixed as H_i and the i-th subchannel signal of the n-th symbol at the transmitter is $X_{n,i}$, then the k-th subchannel signal of the n-th symbol at the receiver is

$$\begin{aligned}
 Y_{n,k} &= e^{-j\omega_k(n\varepsilon + \varepsilon_0)} \cdot \sum_{i=0}^{N-1} H_i \cdot X_{n,i} \cdot \Phi(\omega_k - \omega'_i) \\
 &= e^{-j\omega_k(n\varepsilon + \varepsilon_0)} \cdot H_k \cdot X_{n,k} \cdot \Phi(-\Delta\omega_k) \\
 &\quad + \underbrace{e^{-j\omega_k(n\varepsilon + \varepsilon_0)} \cdot \sum_{i=0, (i \neq k)}^{N-1} H_i \cdot X_{n,i} \cdot \Phi(\omega_k - \omega'_i)}_{ICI}
 \end{aligned} \tag{1-1}$$

where $\omega'_i = \omega_i \cdot \frac{f_s}{\hat{f}_s} \approx \omega_i \cdot (1 + \Delta)$, $-\omega_k(n\varepsilon + \varepsilon_0)$ is an accumulated phase rotation corresponding to the accumulated sampling timing offset, and ε_0 is an initial sampling timing offset when the receiver begins to receive the first symbol. Besides, $\Phi(\omega)$ is the discrete-time Fourier transform (DTFT) of a rectangular window function with N points of 1, that is,

$$\Phi(\omega) = \sum_{n=0}^{N-1} 1 \cdot e^{-jn\omega} = \frac{1 - e^{-jN\omega}}{1 - e^{-j\omega}} = e^{-j(N-1)\omega/2} \cdot \frac{\sin(N\omega/2)}{\sin(\omega/2)}$$

where $\omega = 2\pi fT$.

In equation (1-1), $\Phi(-\Delta\omega_k)$ is the distortion factor of each subchannel, where the amplitude distortion is $\frac{\sin(\pi k \Delta)}{\sin(\pi k \Delta / N)}$ and the phase distortion is $\pi k \Delta (N - 1) / N$.

Since the pilot subchannel transmits a predetermined pilot signal, the following equation can be used to generate an estimated frequency response

of the pilot subchannel:

$$\hat{H}_{n,k} = \frac{Y_{n,k}}{X_{n,k}} = e^{-j\omega_k(n\varepsilon + \varepsilon_0)} \cdot H_k \cdot \Phi(-\Delta\omega_k) + \Gamma_{n,k} \quad (1-2)$$

5 where k is the pilot index, $X_{n,k}$ is the predetermined pilot signal, and $\Gamma_{n,k}$ represents ICI and other noises.

Based on above analysis, the sampling frequency offset can be estimated by the phase error between the estimated frequency responses of two consecutive symbols. If the multi-carrier system employs K pilot subchannels, then the sampling frequency offset can be estimated by: calculating a respective phase difference between the estimated frequency responses of two consecutive symbols for each pilot subchannels; dividing a difference of the respective phase differences by a difference of the corresponding pilot indexes for any two of the K pilot subchannels to generate a plurality of dividing results; and then averaging the dividing results. That is,

$$\Delta\hat{\theta}_{n,k} = \angle\hat{H}_{n,k} - \angle\hat{H}_{n-1,k}, k = \text{pilot index}$$

$$-\frac{2\pi\hat{\varepsilon}_n}{N} = 2\pi\hat{\Delta}_n \frac{N + N_{GI}}{N} = \frac{2}{K(K-1)} \cdot \sum_{\substack{k,l=\text{pilot index} \\ (k \neq l)}} \left(\frac{\Delta\hat{\theta}_{n,k} - \Delta\hat{\theta}_{n,l}}{k-l} \right) \quad (1-3)$$

20 where $\hat{\Delta}_n$ is the estimated sampling frequency offset for the n -th symbol. The accumulated sampling timing offset can then be estimated by using $\hat{\Delta}_n$, that is,

$$\sum_{k=0}^n \hat{\varepsilon}_k = -(N + N_{GI}) \sum_{k=1}^n \hat{\Delta}_k \approx n\varepsilon \quad (1-4)$$

25 When the accumulated sampling timing offset is not large, the

influence of the ICI term $\Gamma_{n,k}$ in equation (1-2) can be ignored, and the phase rotation resulted from the amplitude and phase distortion and the initial sampling timing offset ε_0 can be removed by channel compensation. Thus, in this case, we only need to compensate the corresponding accumulated phase rotation in frequency domain.

However, when the accumulated timing offset is large, in order to prevent the symbol boundary error from causing ISI, it is better to compensate with a specific sampling timing offset ρ in time domain. Here ρ is not exactly the result determined by equation (1-4). ρ is the timing offset which can be practically compensated in time domain in accordance with hardware characteristics, as described below with respect to Fig.4 and Fig.6. Accordingly, in this case, before performing phase compensation in frequency domain, a phase rotation $\omega_k \rho = \frac{2\pi k \rho}{N}$ corresponding to the timing offset ρ , which has been compensated in time domain, is deducted from the accumulated phase rotation of each subchannel. The deducted accumulated phase rotation is then used for phase compensation.

Fig.4 is a block diagram of an apparatus 40 for sampling timing compensation by adjusting a cyclic prefix remover according to the embodiment of the present invention. In this embodiment, a cyclic prefix is used as the guard interval. The apparatus 40 is deployed at the receiver of a multi-carrier system to compensate an accumulated timing offset and phase rotation of a received symbol resulted from sampling frequency offset between the receiver and transmitter. The multi-carrier system includes at least two pilot subchannels, each for transmitting a corresponding pilot signal of a symbol. The cyclic prefix containing latter sampling points of the symbol is prefixed to the symbol. The apparatus 40 includes: a pilot subchannel estimator 41 for generating an estimated frequency response of a received symbol for each pilot subchannel according to the corresponding pilot signal (as shown in equation (1-2)); a timing offset estimator 42, coupled to the pilot subchannel estimator 41, for generating an estimated

sampling frequency offset according to the estimated frequency responses of two consecutive received symbols for the pilot subchannels (as shown in equation (1-3)), and calculating an accumulated timing offset according to the estimated sampling frequency offset (as shown in equation (1-4)); and a
5 phase rotator 44, coupled to the timing offset estimator 42, for compensating the received symbol (i.e. $Y_{n,k}$ in equation (1-1)) according to an accumulated phase rotation corresponding to the accumulated timing offset.

Since the apparatus 40 can perform sampling timing offset compensation by adjusting a cyclic prefix remover, the apparatus 40 further
10 includes: a cyclic prefix remover 109a for removing the cyclic prefix from the received symbol; and a timing controller 43, coupled to the timing offset estimator 42 and the cyclic prefix remover 109a, for delaying or advancing removal of the cyclic prefix performed by the cyclic prefix remover 109a.

When the accumulated timing offset calculated by the timing offset
15 estimator 42 is larger than the sampling interval T_s of the receiver, the timing controller 43 delays the cyclic prefix remover 109a by one sampling point. In response to this timing adjustment, a quantity of T_s (i.e. the specific timing offset ρ for the case of Fig.4) must be deducted from the accumulated timing offset, and an accumulated phase rotation corresponding
20 to the deducted accumulated timing offset is then used for compensation.

When the accumulated timing offset is smaller than $-T_s$, the timing controller 43 advances the cyclic prefix remover 109a by one sampling point. In response to this timing adjustment, a quantity of T_s must be added to the accumulated timing offset, and an accumulated phase rotation corresponding
25 to the added accumulated timing offset is then used for compensation.

By applying the apparatus 40, the embodiment of the present invention provides a method for sampling timing compensation, which includes the steps as shown in Fig.5:

30 51 generating an estimated frequency response of a received symbol signal for each pilot subchannel according to the corresponding pilot signal;

52 generating an estimated sampling frequency offset according to the estimated frequency responses of two consecutive received symbols for the pilot subchannels, and calculating an accumulated timing offset according to the estimated sampling frequency offset;

5 53 determining whether the magnitude of the accumulated timing offset is larger than T_s ; if so, then proceeding to step 55;

54 compensating the received symbol with an accumulated phase rotation corresponding to the accumulated timing offset, and returning to step 51;

10 55 delaying/advancing the cyclic prefix remover 109a by one sampling point to remove the cyclic prefix when the accumulated timing offset is positive/negative;

15 56 re-calculating the accumulated timing offset according to subsequent received symbols, and deducting/adding a quantity of T_s from/to the accumulated timing offset when the accumulated timing offset is positive/negative; and

57 compensating the subsequent received symbol with an accumulated phase rotation corresponding to the deducted/added accumulated timing offset, and returning to step 51.

20 Fig.6 is a block diagram of an apparatus 60 for sampling timing compensation by adjusting a sampling clock of ADC according to the embodiment of the present invention. The apparatus 60 is deployed at the receiver of a multi-carrier system to compensate an accumulated timing offset of a received symbol resulted from sampling frequency offset between
25 the receiver and transmitter. The multi-carrier system includes at least two pilot subchannels, each for transmitting a corresponding pilot signal of a symbol. As shown in Fig.6, the apparatus 60 includes a pilot subchannel estimator 41, a timing offset estimator 42 and a phase rotator 44 which are all similar to the blocks with like numbers in the apparatus 40 of Fig.4.
30 Accordingly, the detailed description of these three blocks is not repeated here.

Since the apparatus 60 can perform sampling timing offset compensation by adjusting a sampling clock of ADC, the apparatus 60

further includes: a clock generator 65 for generating a sampling clock to an ADC 107 of the receiver, wherein the clock generator 65 is phase-adjustable with a minimum adjustable phase shift whose corresponding time interval is T_f , and T_f is shorter than the sampling interval T_s of the ADC 107; and a
5 timing controller 63, coupled to the timing offset estimator 42 and the clock generator 65, for adjusting the clock generator 65 to generate the delayed or advanced sampling clock. It is notable that the clock generator 65 may include a phase-locked loop (PLL) circuit for adjusting the phase of the sampling clock. Besides, T_f may be a fraction of T_s .

10 In the architecture of Fig.6, when the accumulated timing offset calculated by the timing offset estimator 42 is larger than T_f , the timing controller 43 adjusts the clock generator 65 to generate the sampling clock delayed by the minimum adjustable phase shift. In response to this phase adjustment, a quantity of T_f (i.e. the specific timing offset ρ for the case of
15 fig.6) must be deducted from the accumulated timing offset, and an accumulated phase rotation corresponding to the deducted accumulated timing offset is then used for compensation.

On the other hand, when the accumulated timing offset is smaller than T_f , the timing controller 43 adjusts the clock generator 65 to generate the
20 sampling clock advanced by the minimum adjustable phase shift. In response to the phase adjustment, a quantity of T_f must be added to the accumulated timing offset, and an accumulated phase rotation corresponding to the added accumulated timing offset is then used for compensation.

By applying the apparatus 60, the embodiment of the present invention
25 provides a method for sampling timing compensation, which includes the steps as shown in Fig.7:

71 generating an estimated frequency response of a received symbol for each pilot subchannel according to the corresponding pilot signal;

30 72 generating an estimated sampling frequency offset according to the estimated frequency responses of two consecutive received symbols for the pilot subchannels, and calculating an accumulated

timing offset according to the estimated sampling frequency offset;

73 determining whether the magnitude of the accumulated timing offset is larger than T_f ; if so, then proceeding to step 75;

5 74 compensating the received symbol with an accumulated phase rotation corresponding to the accumulated timing offset, and returning to step 71;

75 adjusting the clock generator 65 to generate a clock signal delayed/advanced by the minimum adjustable phase shift when the accumulated timing offset is positive/negative;

10 76 re-calculating the accumulated timing offset according to subsequent received symbols, and deducting/adding a quantity of T_f from/to the accumulated timing offset when the accumulated timing offset is positive/negative; and

15 77 compensating the subsequent received symbol with an accumulated phase rotation corresponding to the deducted/added accumulated timing offset, and returning to step 71.

20 It is notable that if the multi-carrier system employs K pilot subchannels, then in both the steps 52 and 72, the estimated sampling frequency offset and the estimated timing offset can be generated according to equations (1-3) and (1-4) respectively.

25 While the present invention has been shown and described with reference to two preferred embodiments thereof, and in terms of the illustrative drawings, it should be not considered as limited thereby. Various possible modification, omission, and alterations could be conceived of by one skilled in the art to the form and the content of any particular embodiment, without departing from the scope and the spirit of the present invention.